TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 857

INVESTIGATION OF IGNITION AND COMBUSTION PROCESSES OF DIESEL ENGINES OPERATING WITH TURBULENCE AND AIR-STORAGE CHAMBERS

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Forschung auf dem Gebiete des Ingenieurwesens
Vol. 8, No. 6, November-December 1937

Washington
April 1938

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INVESTIGATION OF IGNITION AND COMBUSTION PROCESSES OF DIESEL ENGINES OPERATING WITH TURBULENCE AND AIR-STORAGE CHAMBERS*

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Model tests were conducted at the machine laboratory of the Technical High School of Dresden (1935-36) with the object of investigating the processes in Diesel engines before and during combustion. The tests are a continuation of the work of Holfelder (reference 1). In the present paper some of the results are presented that have been obtained in the study of the effect of air movement on flame development and combustion in engines operating with turbulence chamber and air-storage chamber, respectively.

1. TEST SET-UP

A reciprocating compressor delivers compressed air into a combustion bomb mounted on the cylinder head. The air then flows through a throttle valve over an electric heater back to the suction valve of the compressor, the air circulation being continued until the desired temperature condition of the bomb is attained. At the time the test photographs are taken the throttle valve is closed and the bomb charged, according to the test conditions desired. The injection and combustion process can be observed through two windows in the bomb and photographically recorded. For the purposes of the present investigation, the following modifications were introduced in the test set-up of Holfelder. The fuel pump, instead of being separately driven, was gear-coupled to the compressor so that the start of injection of the pump could be adjusted to any compressor crank angle. In what follows, the injection starting time will be referred to the com-

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*"Untersuchung des Zünd- und Verbrennungsvorganges der nach dem Wirbelkammer- und Luftspeicher- Verfahren arbeitenden Dieselmotoren." Forschung auf dem Gebiete des Ingenieurwesens, vol. 8, no. 6, November-December 1937, pp. 279-284.

pressor crank angle instead of to the pump since the injection lag is slight enough to be within the limits of accuracy of the adjustment. It was necessary to limit the pump speed to 400 r.p.m., on account of difficulties encountered with the photographic apparatus. The pump operated normally through a branch pipe (1.5 mm diameter, 645 mm long) and auxiliary nozzle similar to the injection system leading to the bomb. By an electromagnetically operated interlocking device, a single injection was delivered to the bomb. "Derop" gas oil was used as fuel. The combustion-chamber model was built into the bomb.

2. TESTS ON THE MODEL ENGINE CYLINDER

OPERATING WITH TURBULENCE CHAMBER

Figure 1 shows the model of the turbulence chamber used. In order to keep the passages for the fuel spray the same as those of the Ricardo test engine (Comet E 16) in the machine laboratory, the same diameter was chosen for the turbulence chamber of the model as that of the corresponding engine. It was necessary, however, for obtaining the photographs, to deviate from the spherical shape of the turbulence chamber in the engine and use a cylinder-shaped chamber instead. Through an insert in the bomb, the warm air compressed by the compressor piston was led through a pipe with elliptical end section to the connecting passage, and from the latter into the turbulence chamber. The tests were conducted at various air velocities with different fuel quantities and with two different nozzles, whose functioning had been tested in engine operation.

Test results.- Figure 2 shows the pressure and temperature variation of the air as well as the approximately determined air velocity in the connecting passage - the curves all being referred to the compressor-crankshaft angles. Since for the purposes of these tests, only a general idea of the variation in velocity was required, the flow was assumed in the computation as being inertia-free and with complete pressure and temperature equilibrium. Whereas the air temperature, which was computed from the measured pressures and from the state of the air inducted by the compressor, as well as from the dimensions of the set-up, was subject to only slight variations within the test range, the pressure rise had to be taken into account. The tests showed, however, that the effect of the air velocity was by far predominant over that of the air pressure on the combustion process.

Figures 3 to 8 show some of the flame photographs obtained. The fuel quantity of about 50 mg corresponds approximately to half-load of the engine that was used for comparison. The pictures are arranged below each other, in order of start of injection, referred to crankshaft angle of compressor (360° = top dead center of compressor). The counterclockwise rotation of the fuel spray, corresponding to the air movement, is clearly visible. The rotational motion of the gas masses is particularly well brought out in figures 5 and 6. This motion can be made out also on the other pictures if the transport of the fuel by the air movement is compared from one picture to the next, or the pictures compared with those of figure 8, showing "injections into still air."

The projection of the flame out through the connecting passage into the main combustion chamber of the cylinder, depends not only on the spray penetration but essentially on the direction of pressure drop between turbulence and main chambers. Due to the greater air capacity of the cylinder-shaped model chamber as compared with that of the engine, any considerable amount of projection of the flame is observable only with the greater fuel quantities. Compare figures 5 and 7 corresponding, respectively, to fuel quantities of 50 and 100 mg. The more rapid the rate of decrease of the flow into the chamber without combustion - i.e., the later the injection occurs after the maximum inflow velocity, the greater the flame projection. Since in these model tests the expansion process could not be simulated, it is to be expected that in the case of the engine and particularly also on account of the smaller volume and hence steeper pressure rise in the turbulence chamber, there will be a greater amount of projection of the flame from the turbulence chamber than is shown in these photographs.

Figure 9 gives the numerical results obtained as a function of the start of injection. The ignition lag z_v decreases with later start of injection corresponding to the pressure (or density) and velocity increase of the air, as shown in figure 2. To the ignition lags were added the times of complete combustion z_{Br}. For two different fuel quantities, two curves were obtained which give the total times from start of injection to end of combustion. Consideration of each of the processes leads to the conclusion that, in addition to the atomization of the fuel by the nozzle and further distribution and heating by the air, the fuel is further prepared for combustion by the ignition-lag intervals that become available. Good fuel preparation before combustion and the presence of sufficient combustion air quantities reduce the combustion time.

The shortest total time of ignition lag and combustion is attained when the air velocity during the fuel preparation interval is high. Since the energy of the air vortex in the chamber is greatest when the inflowing air velocity is greatest, the combustion in the chamber will then occur under the most favorable conditions. With start of injection taking place before maximum velocity of inflow, the time for complete combustion remains practically unchanged since the effect of the decreasing ignition lag - that is, shorter time for preparation of the fuel - and the increasing air velocity evidently offset each other. With later injection there is a strong increase in the time taken for combustion, since the interval of fuel preparation becomes still smaller and there is, moreover, a strong slowing down of the air movement. The greater density resulting from the higher pressure is not at all sufficient to offset this effect.

Finally, for different fuel quantities, there were determined the combustion time-intervals, with the other conditions remaining the same (fig. 10). Within the practical range the combustion time increases approximately in proportion to the fuel quantity injected. In addition to the curve for the nozzle DN 12 SD 12, there are also given on the figure the results obtained under the same conditions, using the Bosch nozzle DN 30 S 2. For the latter nozzle the tests gave curves quite similar to those of figure 9, but the combustion time-intervals were longer, as may be seen on figure 10. This nozzle gives a spatially wider fuel distribution since the nozzle has a spray angle of 30°, and a diameter of 2 mm as compared with the 12° angle and 0.5 mm diameter of the DN 12 SD 12 nozzle. The flame photographs which, due to space limitation, are not given here, showed both a change in spray form and a change in the combustion, which appeared less concentrated locally than that shown in the photographs here reproduced.

Insofar as a rapid combustion process is considered to be important, a distribution of the fuel over a larger air space than that corresponding to the local combustion air requirement does not appear to be justified. The speed of combustion will in that case become smaller since the effect of each partial combustion on the successive combustion of the neighboring particles is reduced as a result of the greater spatial separation.

3. TESTS ON MODEL ENGINE OF THE AIR-STORAGE OR AIR-CELL TYPE

In order to observe the movement of the fuel during the ignition lag, the scavenging of the air-storage chamber as well as the combustion process itself, the model shown in figures 11 and 12 was built into the combustion bomb, the design of the model following that of the Henschel-Lanova engine type K. The distance of the nozzle from the air chamber, the arrangement of the air spaces, and approximate sizes and cross sections of the throttles were made to correspond to the engine. The fuel is sprayed through the main combustion space and into two air spaces or cells lying one behind the other and communicating with each other and with the combustion space through throttle passages. The two upper windows in the model provide means for observation into the main combustion chamber. The first air cell is provided with a small window which enables the start of ignition at this position to be followed. The second air cell is provided with two windows, making it possible to observe the quantity of unignited fuel that has reached this position and how the combustion is there developed. The air flows through six orifices on one side of the bomb into the main combustion space, following the same direction as in the comparison engine. The Bosch nozzle DN 4 S9 and the opening pressure of 150 atm., correspond to the engine.

<u>Test results</u>.- For the flame pictures shown in figures 13 and 14, the start of injection occurs approximately within the range of maximum velocity of inflow of air through the first throttle. The fuel quantities correspond to about one-quarter load for figure 13, and full load for figure 14. In the pictures obtained without air movement it was observed that the fuel was partially kept back without motion in front of the mouth of the first

throttle. If the injection, however, occurred as in figures 13 and 14, when there was a strong air movement from the main combustion space to the air-storage chamber, almost the entire fuel was scavenged out from the main combustion space into the air cells. The pictures show clearly that in this case the main combustion space itself takes a very small part in the combustion. The slight exhaust schlieren in the main combustion space indicate that no considerable fuel quantities are carried from the second cell back into the main combustion space, so that incomplete combustion results. With a fuel quantity corresponding approximately to full load (fig. 14), soot formation due to local air insufficiency takes place in the second air cell. In the case of the pictures obtained with still greater fuel quantities, this soot formation is so strong that the windows of the second air cell are completely darkened. The fifth picture of figure 14 shows the small window of the first air cell lit up by the flame passing through. The picture frequency was not sufficient, however, to indicate definitely whether ignition first occurred in the first or in the second air cell.

With later start of injection - that is, with smaller air velocities, there is an increase in the part taken by the main combustion chamber in the combustion process. This is clearly shown by figures 15 and 16, for which the fuel quantities are the same as those of the preceding pictures. A part of the fuel apparently accumulates ahead of the mouth of the first throttle. After ignition the escaping flame drags this fuel along and throws it against the nozzle from which position it spreads laterally and fills the entire main combustion chamber. Soot formation was not observed except for fuel quantities corresponding to an overload of the engine.

Table I gives the numerical results for the two extreme values of the injection times. With later injection the ignition lag decreases somewhat corresponding to the higher air density. The observed ignition lags are greater than those in the engine on account of the lower general temperature level. In general, however - also in the case of the comparison engine - the end of injection occurs before the start of ignition up to about normal load, so that with the injection arrangement here used the jet escaping from the air cell cannot affect the nozzle jet.

Whereas the combustion times in the main combustion space in the case of injection at high air velocity are extremely small, and complete combustion is attained in the second air cell only at part-load fuel quantities, the relations are reversed in the case of injections at low air velocities. The reason for this is to be sought in the distribution of the fuel quantities under the effect of the different air velocities before the start of ignition, as already described. Between these two extreme values of the start of injection, a favorable range will be found which depends not only on the type and quantity of the fuel but also on the injection arrangement chosen.

SUMMARY

The flame photographs obtained with combustion-chamber models of engines operating respectively, with turbulence chamber and air-storage chambers or cells, provide an insight into the air and fuel movements that take place before and during combustion in the combustion chamber. The relation between air velocity, start of injection, and time of combustion was determined for the combustion process employing a turbulence chamber. For the chamber with air cells, various forms of combustiom were observed in the main combustion chamber and in the air cells depending on the air velocity during injection. Due to the lower temperatures and pressures in the model as compared with the engine, greater ignition lags and lower combustion speeds were obtained in the model tests. The proper interpretation of these model tests leads, however, to good agreement with the measurements on the comparison engines. By the direct observation these tests afford, they give a clear picture of the processes that occur in the engine and confirm the significance of engine test results.

Translation by S. Reiss,
National Advisory Committee
for Aeronautics

REFERENCE

1. Holfelder, Otto: Ignition and Flame Development in the Case of Diesel Fuel Injection. Supplement to Forschung auf dem Gebiete des Ingenieurwesens, vol. 6, September-October 1935.

TABLE I. Ignition Lag and Combustion Times for Different Fuel Quantities for the Two Extreme Values of Start of Injection

1.	Start of injection referred to compressor crank angle	°KW	340			357		
2.	Air velocity approximately calculated for first throttle valve	m/s	≈ 190			≈ 25		
3.	Air pressure	atm. abs.	23.5			26.5		
4.	Air temperature	°C	550			550		
5.	Air density	kg/m^3	9.7			10.9		
6.	Ignition lag	s	0.007			0.005		
7.	Fuel quantity	mg	≈ 35	≈ 60	≈ 85	≈ 35	≈ 60	≈ 85
8.	Combustion time in main combustion space	s	0.002	0.003	0.005	0.009	0.024	(soot)0.05
9.	Combustion time in second air-storage cell	s	0.01	(soot)0.03	(soot) ?	0.00	0.017	0.032

		Figure 3	Figure 4	Figure 5	Figure 6
1. Start of injection compressor crank angle	°KW	330	340	350	357
2. Air velocity in connecting passage	m/s	$m \approx 63$	$m = m_{max} \approx 97$	$m \approx 67$	$m \approx 35$
3. Pressure	atm. abs.	$p \approx 11.5$	$p \approx 14.5$	$p \approx 17.5$	$p \approx 19$
4. Temperature	°C	$t \approx 800$	$t \approx 790$	$t \approx 780$	$t \approx 780$

		Figure 13	Figure 14	Figure 15	Figure 16
1. Fuel quantity	mg	$B \approx 35$	$B \approx 60$	$B \approx 35$	$B \approx 60$
2. Start of injection compressor crank angle	°KW	340		357	
3. Air velocity	m/s	$m = m_{max} \approx 190$		$m \approx 25$	
4. Pressure	atm. abs.	$p \approx 23.5$		$p \approx 26.5$	
5. Temperature	°C	$t \approx 550$		$t \approx 550$	

(These tables are part of figures 3, 4, 5, 6 and 13, 14, 15, 16.)

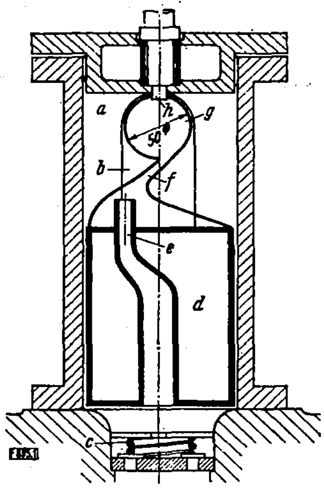
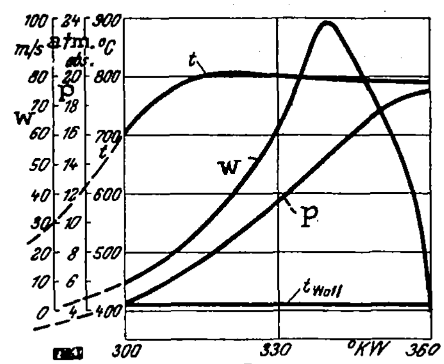


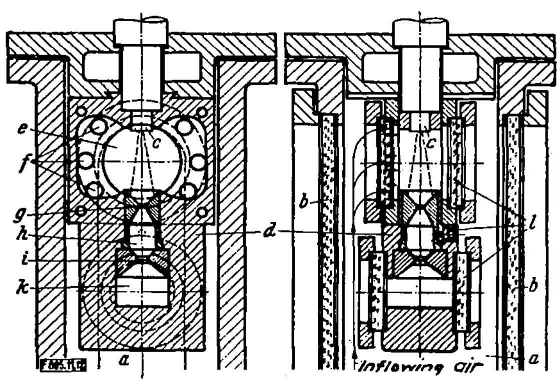
Figure 1.- Turbulence chamber model built into the bomb.(after Ricardo).

a Bomb combustion space.
b Window cut out in bomb.
c Discharge valve of air compressor.
d Air passage from compressor.
f Connecting passage to turbulence chamber.
g Turbulence chamber.
h Fuel valve.
e Air inlet from compressor.

Figure 2.- Pressure p, temperature t and velocity w of air in connecting passage and temperature of turbulence chamber wall t_{wall} as a function of crank angle of compressor.



Compressor crank angle.



Figures 11,12.- Air storage model (Henschel-Lanova type) built into bomb.

a Combustion bomb.
b Window of bomb.
c Bosch nozzle.
d Air storage chamber.
e Main combustion space.
f 6 orifices on one side for incoming air.
g I. Throttle location.
h I. Air cell.
i II Throttle location.
k II Air cell.
l Observation window.

Figure 3.

Figure 4.

Figure 5.

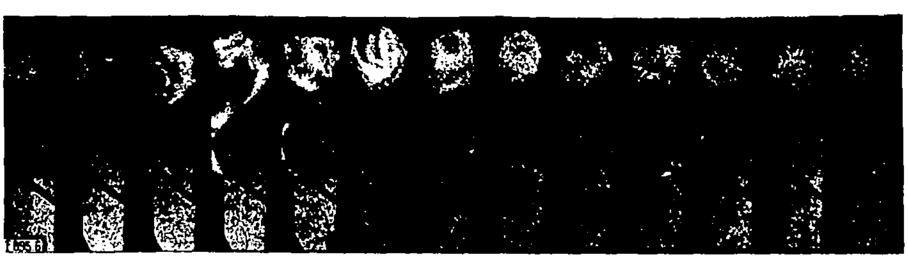


Figure 6.

Figures 3,4,5,6.- Effect of air velocity on fuel distribution and combustion. Turbulence chamber model.
Fuel: Derop gasoil fuel quantity B = 50 mg, Bosch pump PE 1 B 100/100, n = 400 r.p.m., Bosch nozzle DN 12 SD 12. Opening pressure = 85 atm. Seconds per picture = .00245 s.

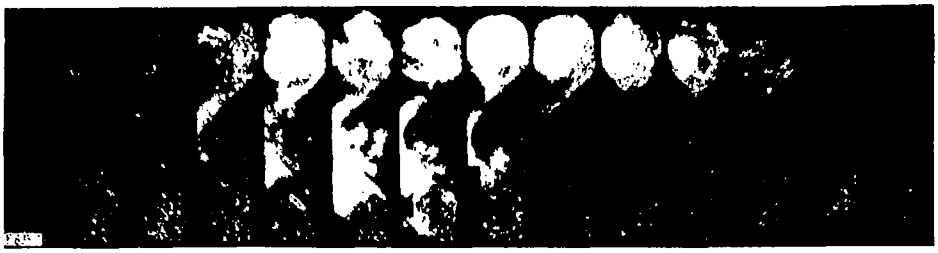
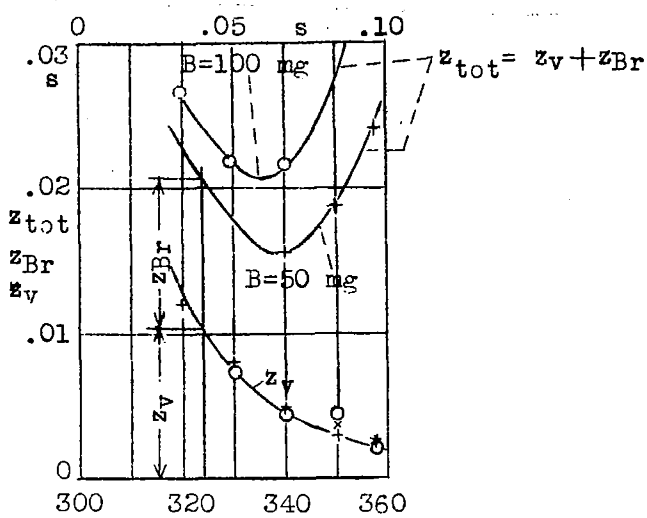


Figure 7.- Effect of fuel quantity on combustion. B = 100 mg as compared with 50 mg of fig.5. Remaining conditions unchanged.

Figure 8.- Injection and combustion in still air, w = 0, p = 21 atm. abs, t = 550° C. Remaining conditions unchanged.



Start of injection referred to compressor crank angle.

Figure 9.- Ignition lag time z_v, time of combustion z_{Br}, and total time z_{tot} as functions of start of injection referred to compressor crank angle. Fuel: Derop gasoil. Bosch pump PE 1B 100/100, n=400 r.p.m. Bosch nozzle DN 12 SD 12, valve opening pressure 85 atm.

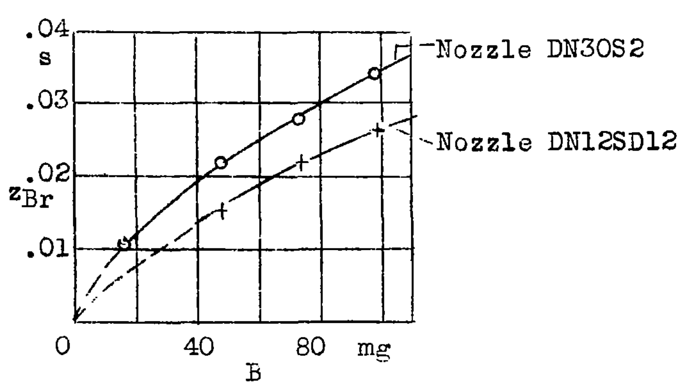


Figure 10.- Time of combustion as a function of fuel quantity B for two different Bosch nozzles. Start of injection at 350° crank angle of compressor. w= 67 m/s,(220 ft/sec.),p = 17.5 atm. abs, t = 780° C.

Figure 13.

Figure 14.

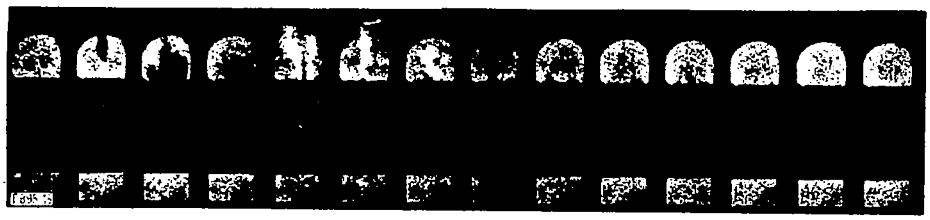


Figure 15.

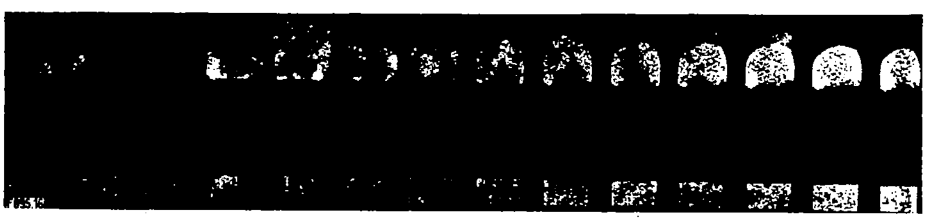


Figure 16.

Figures 13,14,15,16.- Effect of fuel quantity and air velocity on fuel distribution and combustion in air storage type combustion chamber.

Fuel: Derop gasoil. Bosch pump PE 1 B 100/100, n = 400 r.p.m. Bosch nozzle DN 4 S 9, valve opening pressure = 150 atm. seconds per picture = .0024 s.